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Magnetic resonance imaging apparatus and method

Technical field

The present invention relates to a magnetic resonance imaging (MRI) apparatus for imaging nuclear density distribution or relaxation time distribution by measuring nuclear magnetic resonance (NMR) signals emitted from hydrogen atoms or phosphorus atoms in an examined object.

Background of Invention

An EPI (echo planar imaging), burst sequence and the like have been known as a fast imaging method using an MRI apparatus, where a plurality of echo signals is measured at one excitation of spins, and are used for a three-dimensional measurement or functional measurement in which many images are obtained continuously. As an application of these methods, a multi-shot EPI that measures a set of data at a plurality of shots (excitation) has been also known.

Echo signals obtained by such a fast imaging method are likely to be influenced by eddy currents caused by gradient magnetic fields or inhomogeneities in a static magnetic field, and therefore are subjected to phase correction using a correction data (for example, Japanese Patent Application Kokai 5-31095). For the correction data, scan data obtained by performing a measurement (pre-scan) similar to a main measurement is used. The pre-scan is carried out prior to the main measurement without a slice-encoding gradient magnetic field or a phase-encoding gradient magnetic field.

An SSFP (Steady State Free Precession) measurement has been also known as an application of MRI. The SSFP measurement obtains echo signals successively with a short repetition time TR relative to a longitudinal relaxation time of an examined object while changing a slice-encoding gradient magnetic field or phase-encoding gradient magnetic field. The resulting echoes are in a steady state free precession.

The SSFP measurement is suitable for a three-dimension measurement, since it measures echoes with a short repetition time while changing a condition of applying gradient magnetic fields, and its combination with the fast imaging method such as EPI is proposed (for example, SSFP-EPI).

The inventors of the present invention tried to apply the aforementioned signal correction using correction scan data to the SSFP-EPI. However, it was found that good correction results could not be obtained and artifact appeared in images. The reason would be thought as follows. In correction using the pre-scan data, conditions such as eddy currents and inhomogeneities in the static magnetic field should be the same at a time of acquisition of the pre-scan data and a time of acquisition of data for forming images (main scan data). However, eddy currents, which generate at gradient magnetic field coils, vary according to a time constant. The variations of eddy currents are not a serious problem in a measurement with a long repetition time but are problematic in the SSFP measurement because of its short repetition time. In addition, since a phase

rotation amount of spins also depends on a degree of saturation of spins, it can be changed gradually till spins become to be in a steady state in the SSFP-EPI. Such phase changes continuing till the steady state cannot be corrected by the conventional phase correction method using the pre-scan data.

Accordingly, an object of the present invention is, in the SSEP measurement, to eliminate essential causes of artifacts due to change of physical phenomena over time such as eddy currents by gradient magnetic fields, variations of residual magnetic field, and to provide MR images having good quality and no artifact.

Disclosure of Invention

In order to solve the above-mentioned problems, an MRI apparatus of the present invention performs a pre-scan for obtaining data for correcting variations of static magnetic field inhomogeneities and/or eddy currents prior to a main measurement scan, and corrects data obtained by the main measurement scan based on data obtained by the pre-scan.

Specifically, the MRI apparatus of the present invention comprises magnetic field generating means for producing nuclear magnetic resonance in an object to be examined, detecting means for detecting nuclear magnetic resonance signals emitted from the object, control means for controlling the magnetic field generating means and detecting means, computing means for visualizing morphology or functions of the examined object using the nuclear

magnetic resonance signals detected by the detecting means, and a display means for displaying the computed results as images, wherein the control means operates so that a plurality of correction data are acquired periodically at a predetermined interval and image-forming data are continuously acquired between acquisitions of the correction data, and the computing means produces a correction data group, which corresponds to acquisition time of the image-forming data, using the correction data and corrects the image-forming data using the correction data group corresponding to the acquisition time.

The MRI apparatus of the present invention comprises magnetic field generating means for producing nuclear magnetic resonance in an object to be examined, detecting means for detecting nuclear magnetic resonance signals emitted from the object, control means for controlling the magnetic field generating means and detecting means, computing means for visualizing morphology or functions of the examined object using the nuclear magnetic resonance signals detected by the detecting means, and display for displaying the computed results as images, wherein the control means continuously performs a step of acquiring a plurality of nuclear magnetic resonance signals as image-forming data at one excitation and also performs a step of acquiring correction data a number of times at a desired interval during the continuous steps, and the computing means comprises means for producing a correction data group, which includes changes during the interval, using a plurality of the correction data acquired at a desired

interval and means for correcting image-forming data using a correction data from among the correction data group corresponding to acquisition time of the image-forming data.

An MRI method of the present invention comprises a step A of acquiring image-forming data consisting of a plurality of nuclear magnetic resonance signals at one excitation, a step B of repeating the step A while changing a slice-encoding gradient magnetic field and/or phase-encoding gradient magnetic field, a step C of repeatedly acquiring correction data at a desired interval during repetition of the step A, a step D of producing correction data corresponding to acquisition time of image-forming data acquired between acquisition of one correction data and acquisition of the next correction data using at least two correction data, and a step E of correcting the image-forming data using correction data from among the correction data produced in the step D, which corresponds to acquisition time of the image-forming data.

The interval of acquiring the correction data may be the same as a time required for collecting image-forming data of one image or may be a time required for collecting image-forming data of plural images.

According to the MRI apparatus and method, correction data including temporal variations between acquisition of one correction data and acquisition of the next correction data is produced. When plural image-forming data are acquired between these two correction data, each of the image-forming data is corrected using correction data corresponding to its acquisition time (estimated correction

data).

Thus, the image-forming data consisting of a plurality of nuclear magnetic resonance signals is corrected using corresponding correction data including temporal variations from among the correction data group, and consequently phase correction can be done taking account of temporal variations of physical phenomena such as influence of spin saturation, eddy currents by gradient magnetic fields, changes of residual magnetic fields so that artifact caused by the phenomena can be prevented.

The plural correction data are preferably acquired without a phase-encoding magnetic field, or acquired while imparting with a phase-encoding magnetic field and readout magnetic field having a polarity opposite to that used for main scan data. When the phase-encoding magnetic field is not applied, the correction data consists of nuclear magnetic resonance signals of the same number as that of image-forming data obtained in the step A. When the phase-encoding magnetic field is applied, the correction data consists of nuclear magnetic resonance signals of the same number as the phase-encode number for the image-forming data. In this specification, these two are referred as correction scan data.

In a preferred embodiment of the present invention, the step B is carried out with a repetition time significantly shorter than a longitudinal relaxation time of the examined object. This enables to obtain a series of main scan data in a steady state free precession.

In this case, each of correction scan data is

acquired preferably with a interval equal to the aforementioned TR before and after acquisition of main scan data. As a result, a steady state free precession can be maintained during acquisition of the correction scan data and degradation of image contrast can be prevented.

Brief explanation of drawings

Figure 1 is a schematic view of an embodiment of the MRI method of the present invention. Figure 2 is a flowchart of signal processing according to the MRI method of the present invention. Figure 3 is a timing chart of an EPI sequence to which the present invention is applied. Figure 4 is an overall diagram of an MRI apparatus to which the present invention is applied. Figure 5 is a flowchart of signal processing according to another embodiment of the MRI method of the present invention. Figure 6 is a schematic view of another embodiment of the MRI method of the present invention.

Preferred embodiment of Invention

Preferred embodiments of the present invention will now be explained hereinafter. Figure 4 is an overall diagram of an MRI apparatus to which the present invention is applied. The MRI apparatus comprises a magnet 402 generating a static magnetic field in a space around an object to be examined (patient) as magnetic field generating means, gradient magnetic field coils 403 which generate gradient magnetic field in the space, an RF coil 404 for generating a high frequency magnetic field in an

area within the object, and an RF probe 405 for detecting MR signals emitted from the object 401. In addition, it is provided with a signal processor 407 for processing the detected MR signals to transform to image signals, a display 408 for displaying images showing morphology, function and spectrum of the object based on the image signals inputted from the signal processor 407, and a bed 412 on which the patient lies.

The gradient magnetic field coils 403 consist of gradient magnetic field coils of three direction X, Y, Z, each of which generates a gradient magnetic field corresponding to signals from a power supply 409. The RF coil 404 generates a high frequency magnetic field corresponding to signals from an RF transmitter 410. Signals from the RF probe 405 are detected by a signal detector 406 and processed by the signal processor 407. The power supply for gradient magnetic field 409, RF transmitter 410 and signal detector 406 are controlled by a controller 411 according to a timing chart called a pulse sequence.

In the MRI apparatus of this embodiment, the controller 411 performs a fast imaging sequence according to a multi-shot EPI. Specifically, a pulse sequence in which a plurality of nuclear magnetic resonance signals for image-forming data is acquired at one excitation is repeated to collect a series of image-forming data (main scan data). During acquisition of a series of the main scan data, application of an RF magnetic field and gradient magnetic fields and acquisition of signals are controlled

so that correction scan data are obtained at an approximately same interval (referred simply as same interval). The repetition time TR is so determined that a series of the scan data (main scan data and correction scan data) can be obtained in a steady state free precession.

The signal processor 407 performs ordinary signal processing required for image reconstruction and, in addition, has a function of producing correction data including temporal changes using a plurality of correction scan data obtained at a predetermined interval and a function of correcting main scan data using correction data corresponding to acquisition time of the main scan data.

The display 408 displays images produced by reconstruction of the main scan data which has been corrected using correction data.

Next, an embodiment of the MRI method of the present invention, which is applied to a two-dimensional SSFP-EPI, will be explained. Figure 1 is an explanatory view of data acquisition and correction in this embodiment, where the axis of abscissas is time. In Figure 1, a number 13 indicates a Fourier transform in the readout direction, a number 14 indicates phase correction and a number 16 indicates a Fourier transform in the phase-encoding direction. Figure 2 is a flowchart showing procedures conducted by the signal processor 407.

In the measurement, a first pre-scan (scan for obtaining correction data, referred as correction scan hereinafter) is carried out prior to a main measurement to obtain correction scan data 11. Then the main measurement

is carried out to obtain main scan data 12 (121, 122, 123, 124)(step 64). During the continuous measurement of main scan data 12, a second, third···correction data 11 (111, 112, 113···) are repeatedly acquired at a fixed interval (step 61). These correction scan data 11 are used for phase correction of main scan data (steps 70, 62, 63), which will be explained later.

A pulse sequence used for the main measurement may be, for example, an EPI sequence shown in Figure 3. That is, an RF pulse 201 is applied to an object to be examined, which includes detectable magnetization, together with a gradient magnetic field pulse 202 for selecting a slice to be imaged. Then, a pulse 203 for imparting a phase-encoding offset and a pulse 205 for imparting a readout gradient magnetic field offset are applied. Thereafter, gradient magnetic field pulses 206 with alternating polarity are applied successively.

A shape of the gradient magnetic field pulse 206 is trapezoid. Simultaneously with the gradient magnetic field pulses 206, discrete phase-encoding gradient magnetic field pulses 204 are applied. Phase-encoded echo signals 207 are generated in each period of alternating readout gradient magnetic fields 206 and are collected as a sample during a time range 208 to obtain time-series data. Although five or more of echo signals are acquired in Figure 3, the number n of signals can be less.

Provided that a number of echo signals measured at one excitation (one shot) is n and a number of data in the phase-encoding direction is N, one set of two-dimensional

data can be obtained by N/n time repetitions (N/n shots) of the sequence shown in Figure 3.

In the correction scan, echo signals of the same number are measured using a similar sequence shown in Figure 3 without a phase-encoding gradient magnetic field Ge. Alternately, correction scan data may be acquired by applying phase-encoding gradient magnetic fields together with reversed readout gradient magnetic field Gr. In this case, correction scan data of the same number as the shot number of the main measurement are acquired.

In the embodiment shown in Figure 1, a set of two-dimensional data is obtained by 10 shots and one correction scan data 11 is obtained every 10 shots. An interval of obtaining the correction scan data 11 may be shorter or longer than in this embodiment.

The repetition time of the correction scan data 11 and that of main scan data 12 should be fixed and significantly shorter than a longitudinal relaxation time of spins, for instance, about 10ms.

Next, based on the thus periodically obtained plural correction data, a estimated phase rotation amount 19 for each acquisition time of the main scan data is calculated (step70). This calculation may be done by linear interpolation using adjacent correction scan data or may be done by a known interpolation technique. This calculation provides a group of correction data (correction data group), which consists of estimated correction data for each acquisition time of the main scan data. In the illustrated example, estimated correction data corresponding to main

scan data of 10 shots acquired between acquisitions of the correction scan data 111 and 112 are obtained.

In the next step, for the correction data group, data arrangement is reversed depending on the polarity of the gradient magnetic field pulse (step 62). This is a common process in EPI. In the sequence of Figure 3, for example, the first echo is acquired with a negative polarity gradient magnetic field pulse Gr and the second echo is acquired with a positive polarity gradient magnetic field pulse Gr. Accordingly, arrangement of the first echo with a negative polarity is reversed in the time direction and that of the second echo is not reversed.

After the abovementioned reversal, the correction data is subjected to a Fourier transform in the readout direction for each echo and stored in a memory of the signal processor 407 as a complex data map on a two-dimensional hybrid space (position in the readout direction vs echo acquisition order)(step 63).

For the main scan data, similarly to the correction scan data, data arrangement is reversed for each echo depending on the polarity of the gradient magnetic field pulse (step 65). Then, each echo is subjected to a Fourier transform 13 in the readout direction and stored in a memory of the signal processor 407 as a complex data map on a two-dimensional hybrid space (step 66).

Thereafter, the Fourier transformed main scan data is corrected using the Fourier transformed correction data. In the phase correction 14, the correction data corresponding to acquisition time of the main scan data of each shot is

used (step67). Specifically, the main scan data 121 is corrected with the correction data 191 and the main scan data 122 is corrected with the correction data 192 respectively to obtain the corrected main scan data 15.

Such phase correction enables to eliminate influence of inevitably unsatisfactory instrumental adjustment at the signal acquisition moment such as residual offset components of gradient magnetic fields, inhomogeneities in the static magnetic field caused by an object under examination. Particularly, since a phase rotation amount at the acquisition time of main scan data is estimated and the estimated value is used for correction of the main scan data, variations of the phase rotation depending upon a degree of spin saturation can be corrected. In addition, even when phase variations caused by eddy currents of gradient magnetic fields or static magnetic field inhomogeneities change over time, correction can be done accurately.

Finally, 10 sets of the corrected main scan data 151、152、153…are collected and subjected to a Fourier transform 16 in the phase-encoding direction to obtain a two-dimensional MR image (step 68) and the image is displayed (step 69). The image has good quality since residual offset components of gradient magnetic fields, inhomogeneities in the static magnetic field caused by an examined object and their variations over time have been corrected.

Since the main scan is carried out continuously between correction scans performed at a predetermined interval, a plurality of two-dimensional MR images can be obtained

successively in a time course. The plural two-dimensional MR images may be images of an identical slice or may be images of different slices. When images of different slices are to be obtained, an RF pulse 201 and/or slice selecting gradient magnetic field 202 in the pulse sequence of Figure 3 is changed every 10 shots to acquire echo signals 207 from different slices.

If the identical slice is measured successively, images of the slice are successively displayed on the display 408. These successive images may be utilized for observation of function of an organ. If images of different slices are obtained, the images of plural slices may be displayed simultaneously on the display 408 and thus a broad region can be observed at the same time. These manners of measurement and displaying of images may be employed in a suitable combination. For example, during a continuous imaging of an identical slice, imaging of an adjacent slice or intersecting slice may be performed, and the successively obtained images of one slice and images of plural slices may be displayed one by one. Alternately, images of plural slices are displayed simultaneously and repeatedly, and are updated successively.

In the abovementioned embodiment, it has been explained that a phase rotation amount of the main scan data is estimated for each acquisition time based on the obtained raw correction scan data. However, estimation of the phase rotation amount of the main scan data for each acquisition time can be done based on the correction scan data after a Fourier transform. The flowchart of such procedures is

shown in Figure 5.

In the embodiment shown in Figure 5, the correction scan data is acquired periodically during acquisition of the main scan data similarly to the flowchart shown in Figure 2 (step 61). However, the correction scan data is subjected to a Fourier transform prior to estimation (step 70) of the correction data for the main scan data of each acquisition time. That is, first, reversal of data arrangement is carried out corresponding to the polarity of gradient magnetic field pulse (step 62) and then a Fourier transform of each echo is carried out in the readout direction (step 63).

For the thus Fourier transformed data, correction data corresponding to acquisition time of the main scan data is calculated. This calculation may be also performed by linear interpolation of the Fourier transformed data, which have been acquired before and after the acquisition time of the subjected main scan data.

The thus calculated correction data group is stored as a complex data map on a two-dimensional hybrid space and used for phase correction 14 of the main scan data which has been subjected to the Fourier transform in the readout direction. In the phase correction, the main scan data is corrected using correction data corresponding to acquisition time of the main scan data one by one (step 67). In this case too, similarly to the case of Figure 2, even temporal variations in apparatus characteristics, influence of eddy currents or spin saturation can be corrected precisely.

The MRI method of the present invention has been explained with respect to its application to a two-dimensional measurement. The present invention may be applied to a three-dimensional measurement in the same manner.

Figure 6 shows another embodiment of the MRI method according to the present invention, which is applied to a three-dimensional measurement. This embodiment is same as the embodiment shown in Figure 1 in that the correction scan data 11 is acquired at a predetermined interval during acquisition of the main scan data 12, and that the correction scan data and the main scan data are measured with the same repetition time TR. In the three-dimensional measurement, however, a step of collecting a series of main scan data is repeated while changing intensity of a slice-encoding gradient magnetic field. In the illustrated example, a slice-encode is changed every acquisition of main scan data of 10 shots.

In this embodiment too, a series of the main scan data 12 is corrected based on correction data corresponding to the acquisition time from among the correction data group 19, which are estimated from two correction scan data obtained before and after the acquisition time (for example 111 and 112). The correction data group 19, which is a set of correction data for each acquisition time of the main scan data, may be calculated by interpolation using raw correction scan data as shown in the figure, or may be calculated using the Fourier transformed data obtained by performing a Fourier transform 13 on the raw correction

scan in the readout direction as shown in Figure 5. When the correction data is estimated from the raw correction scan data, each correction data is subjected to a Fourier transform in the readout direction and used for the phase correction 14.

The main scan data is also subjected to a Fourier transform 13 in the readout direction and corrected based on the correction data 19 of each acquisition time to obtain the corrected main scan data 15. In the three-dimensional measurement, the main scan data 15 obtained with a slice-encoding gradient magnetic field of same intensity are subjected to a Fourier transform 16 in the direction of the second axis (phase-encoding direction) and the thus transformed data is further subjected to a Fourier transform 17 in the direction of the third axis (slice-encoding direction) to obtain a three-dimensional image. In this case, similarly to the two-dimensional measurement, variations of phase rotation depending on a degree of spin saturation can be corrected and phase changes caused by eddy currents of gradient magnetic fields and static magnetic field inhomogeneities can be also corrected.

The thus obtained three-dimensional images may be displayed on the display 408 as a projection image after projection process or as a tomogram of a desired slice. Alternately, plural two-dimensional images obtained by performing a Fourier transform of the main scan data 15 in the phase-encoding direction may be displayed successively as time-series images or simultaneously on one screen, as explained in the manners of imaging and displaying of the

two-dimensional image shown in Figure 1. However, the main scan data 15 consists of signals from a slab having a certain thickness and the resolution degree of images depends on the slab thickness. Accordingly, when two-dimensional images produced from the main data 15 obtained by the three-dimensional imaging are displayed, the slab thickness should be adjusted suitably.

Although an interval of acquisition of the correction scan data and that of stepping the slice encode are set to be equal in Figure 6, they are not necessarily equal. In a case that more accurate correction is required, a plurality of correction scan data may be acquired within the same slice-encoding step.

In the aforementioned embodiments, a multi-shot EPI has been exemplified but the present invention is similarly applied to a single shot EPI. In the single shot EPI, each of the main scan data 121,122…consists of echoes necessary for forming one image and the correction scan data consists of the same number of echoes.

Similarly to the embodiments of Figures 1 and 6, the correction data corresponding to acquisition time of the main scan data is produced using a series of correction scan data obtained before and after the acquisition of the main scan data, and the main scan data, which has been subjected to a Fourier transform 13 in the readout direction, is phase-corrected (14) using the corresponding correction data. In the single shot EPI, however, the thus corrected scan data 151、152… can be reconstructed to one image by performing a Fourier transform in the phase-

encoding direction.

If the main scan data is imparted with a slice encode, 3D-image data 18 can be obtained by collecting the data of number equal to the slice-encode number, which has been subjected to a Fourier transformed in the phase-encoding direction, and by performing a Fourier transform in the slice-encoding direction.

Although the two-dimensional or three-dimensional EPI has been explained hitherto, the present invention can be applied to any conventional sequence including correction of phase rotation using pre-scan data. For instance, it can be applied to a two-dimensional or three-dimensional multi-shot EPI sequence of Time Reverse type, two-dimensional multi-shot spiral scan sequence, three-dimensional GRSE (gradient and spin echo sequence), hybrid burst sequence or the like.

Industrial applicability of Invention

In a sequence including phase correction using correction scan data, the correction scan data is obtained periodically and the phase rotation amount at each acquisition time of the main scan data acquired between the adjacent correction scan data is estimated. The main scan data is corrected using the thus estimated phase rotation amount. As a result, MR images having high quality and no artifact can be obtained even in a condition where the phase variations of signals change due to temporal variations of eddy currents or spin saturation state.